



# *Ex Situ Treatments of Aqueous Film-Forming Foam Impacted Water*

Fourth International Symposium on Bioremediation and  
Sustainable Environmental Technologies

Session: F4. Innovative Treatment Technologies for PFAS Compounds

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# Acknowledgements

*For every zone of your plume, we've got you covered!*

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Essen, Germany



**Ziltek Pty Ltd**  
Thebarton, South Australia, Australia



**Cornelsen Umwelttechnologie GmbH**  
Essen, Germany

*"It's better to hang out with people better than you. Pick out associates whose behavior is better than yours and you'll drift in that direction." Warren Buffet*

# *Ex-Situ* Treatment Applications

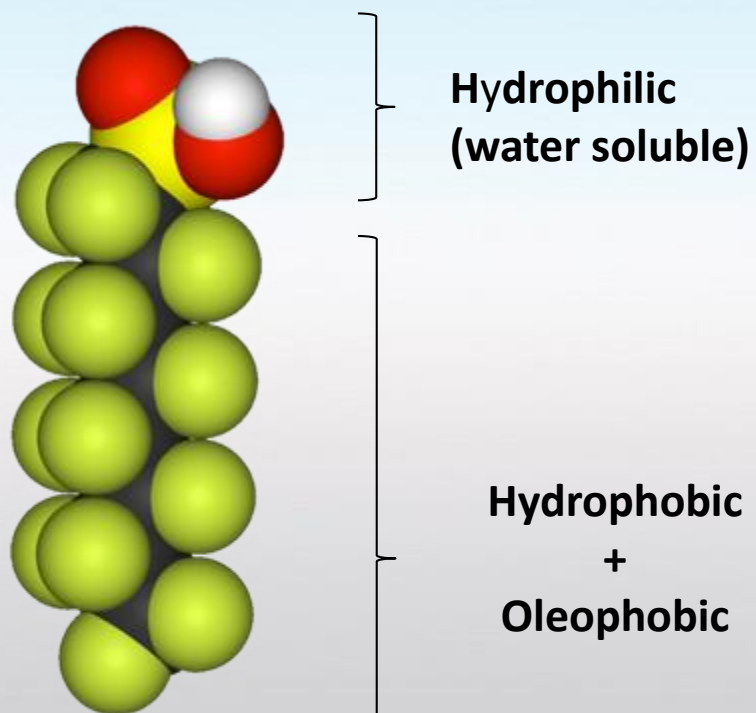
*For every zone of your plume, we've got you covered!*

- Soil remediation
- Groundwater hot spots and plumes
- Complex groundwater chemistries
- Recovered fire fighting water
- Drinking water POE systems



# Physicochemical Properties

*For every zone of your plume, we've got you covered!*



PFOS

Kissa (2001), *Fluorinated Surfactants and Repellents*, 2<sup>nd</sup> ed.  
Slide from Daniel P. McInnis, Ph.D., University of Minnesota

# The Challenge

## Behavior

Physicochemical Properties		
Solubility	PFOS	PFOA
Solubility in Surface Water (mg/l)	370	9,500
Evaporation	PFOS (K salt)	PFOA (NH <sub>4</sub> salt)
Vapor Pressure (Pa, at 20 °C)	$3.31 \times 10^{-4}$	$13 \times 10^{-3}$

## Strong covalent bond

- Second strongest single bond in organic chemistry



- Resistant to biological degradation

# The Challenge

*For every zone of your plume, we've got you covered!*

- Existing treatment processes ineffective / limited
- GAC & ion exchange limited to longer chain PFASs
- Poor efficiency
- Influence of background chemistry
- Waste disposal costs

# Limited Remediation Options

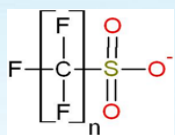
*For every zone of your plume, we've got you covered!*

- Extremely resistant to thermal, chemical and biological degradation processes.
  - Incineration – requires high temp (PFOS >1,100 °C)
  - Biological and chemical – efficacy not proven
- Landfill – prohibited or require pre-treatment
- GAC – proven for water, but doesn't treat full suite

# Polar Pollutants

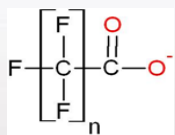
*For every zone of your plume, we've got you covered!*

## Perfluoroalkyl Sulfonates (n = 2-10)

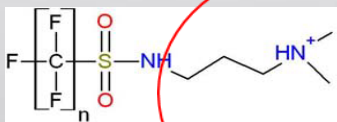


**Anions**

## Perfluoroalkyl Carboxylates (n = 2-13)

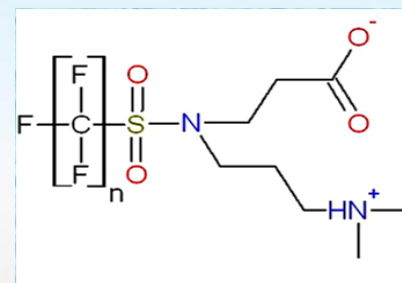


## Perfluoroalkyl Sulfonamido Amines (n = 3-8)

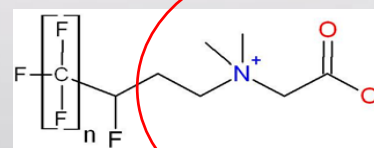


**Cations**

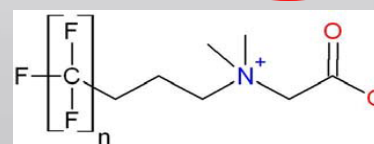
## Perfluoroalkyl Sulfonamide Amino Carboxylates (n = 3-8)



## Fluorotelomer Betaines (n = 5,7,9)



**Zwitterions**



After: Per- and Polyfluoroalkyl Substances (PFAS) in AFFF Formulations and Groundwater, Jennifer A. Field, Ph.D., April 2015. <http://www.denix.osd.mil/edqw/home/april-2015-emdq-workshop/april-2015-what-s-new/field/>



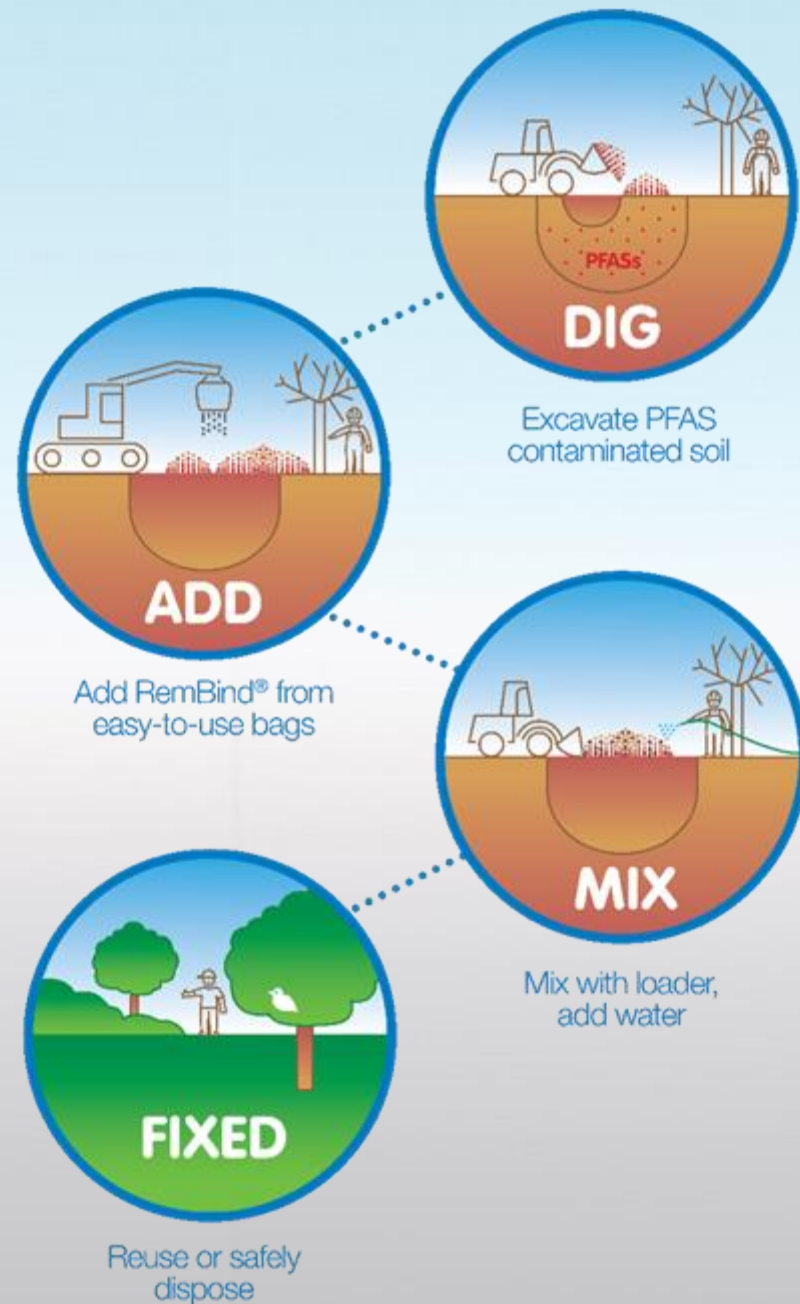
# Treatment Options

*For every zone of your plume, we've got you covered!*



# RemBind®

- Rapid
- Safe
- Permanent



# What is *RemBind*®?

*For every zone of your plume, we've got you covered!*

- Powdered reagent that binds to organic contaminants in soil/water to prevent leaching
- Chemical fixation or immobilization
- Binds to range of contaminants including TPH, PAH, and PFASs
- US Patent 8,940,958



# How Does *RemBind*® Work?

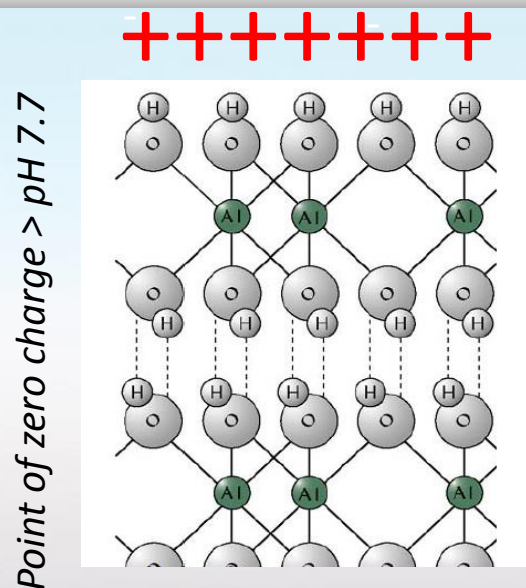
*For every zone of your plume, we've got you covered!*

- Main ingredients:
  - Activated carbon
  - Aluminium hydroxide (amorphous)
  - Organic matter and additives
- Large surface area with mixed charges
- Chemical and physical interactions



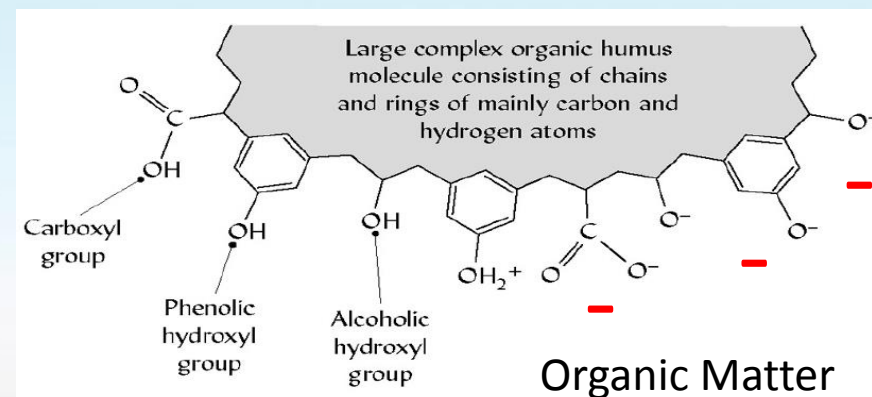
# Mechanisms of Action

*For every zone of your plume, we've got you covered!*



Aluminium Hydroxide  
(Amorphous)

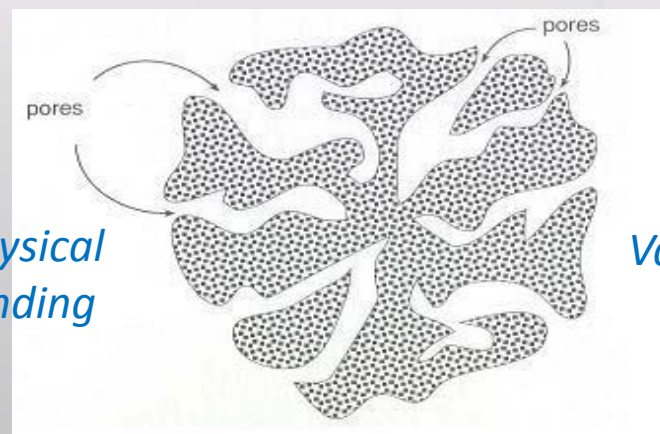
*Electrostatic  
interactions*



*Hydrophobic Interactions*

*Physical  
Binding*

*Van der Waals*



Activated Carbon

# PFAS Excavation Project

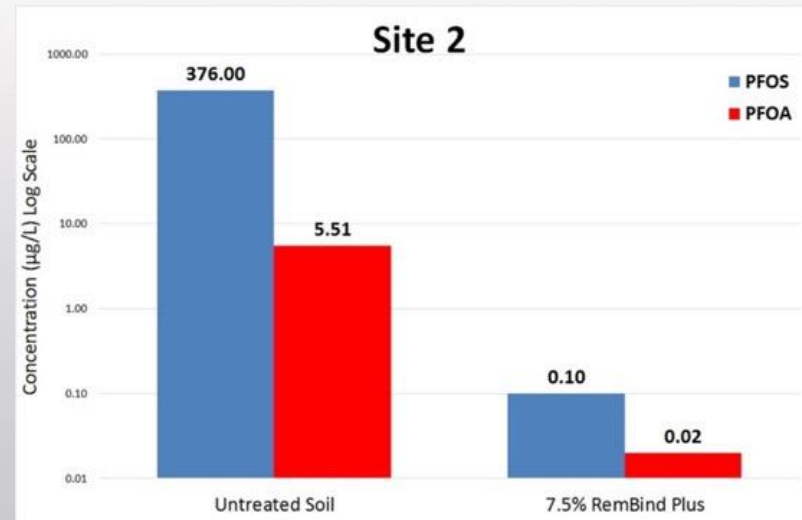
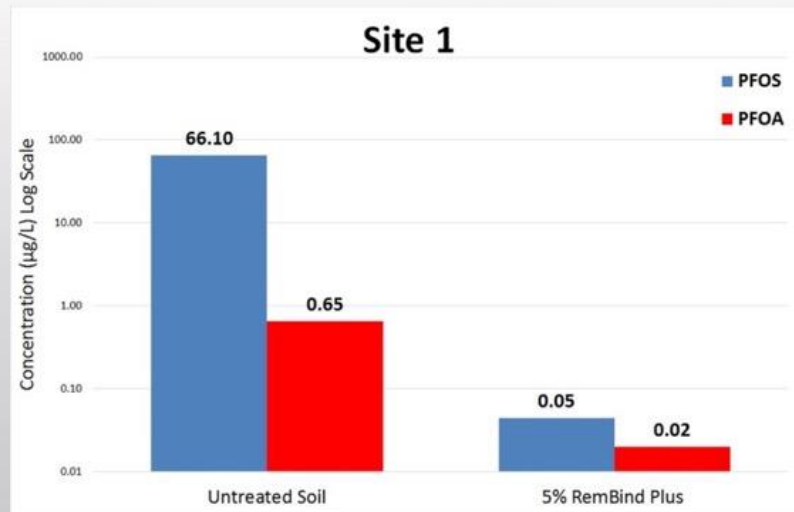
*For every zone of your plume, we've got you covered!*



# Treatability Study: PFOS in Soil

*For every zone of your plume, we've got you covered!*

- Two commercial airport sites in Australia
- All lab work **independently** audited
- Site soils mixed with *RemBind*® or *RemBind*® Plus at various addition rates



\* Soil leachates prepared using the Toxicity Characteristic Leaching Procedure (TCLP)

# How Stable is Binding?

*For every zone of your plume, we've got you covered!*

- Multiple Extraction Procedure (US EPA 1320)
- Simulates 1,000 years acid rain in an improperly designed sanitary landfill
- Site 1 Results 5% RemBind<sup>®</sup> Plus
  - <0.02 µg/L



# RemBind<sup>®</sup> used to Immobilize PFAS in Water

*For every zone of your plume, we've got you covered!*

- **Independent** evaluation carried out by a testing company in Germany - Sensatec
- Passed PFAS contaminated water (1.8 mg/L) through a column, up to 100 pore volumes
- Compared *RemBind*<sup>™</sup> Plus with activated carbon
- Evaluated short- and long-chain PFASs



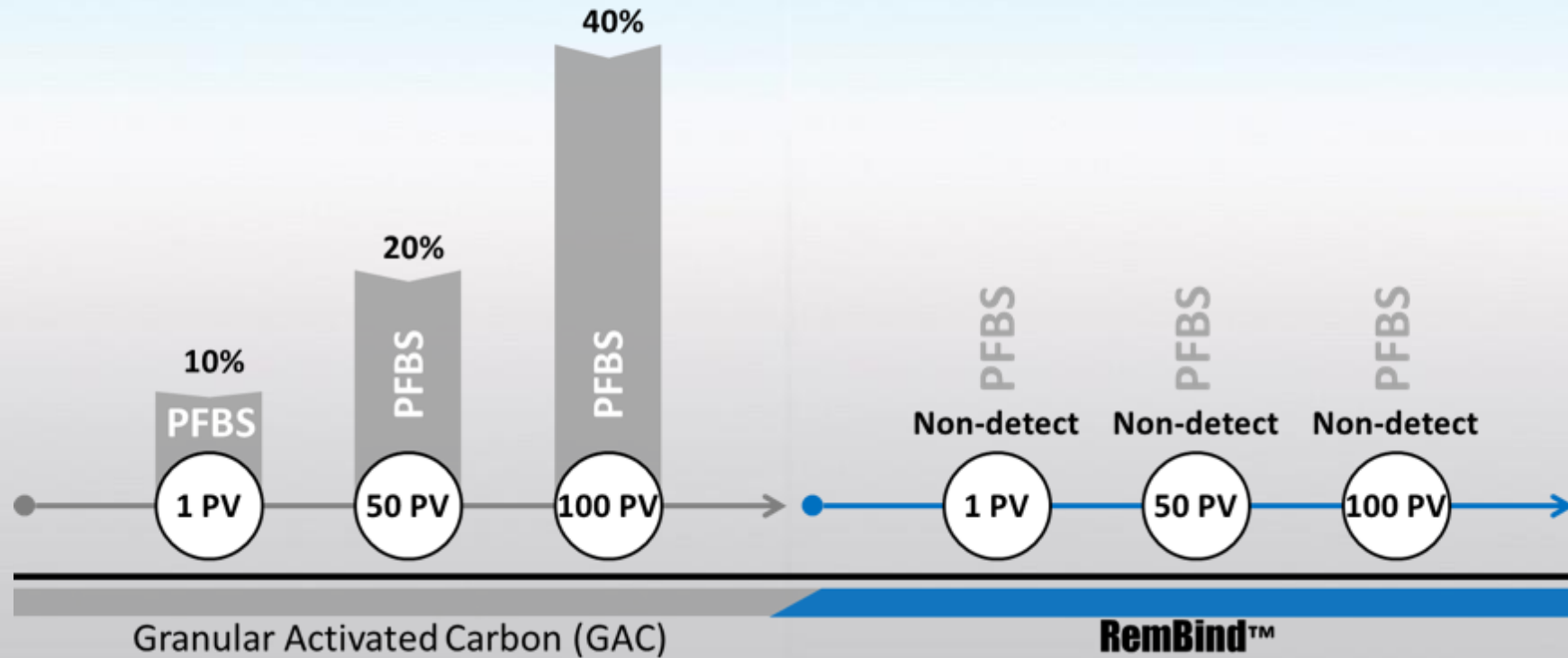
Test Compound	C-F Chain Length	Terminal Group
PFOS	n=8	Sulfonic acid
PFOA	n=7	Carboxylic acid
PFBS	n=4	Sulfonic acid
PFBA	n=3	Carboxylic acid

# RemBind® Outperforms Activated Carbon

*For every zone of your plume, we've got you covered!*



## Breakthrough results for potassium perfluorobutane sulfonate (PFBS)



# Using *RemBind*® to remove short- and long-chain PFAS from water

*For every zone of your plume, we've got you covered!*

## Summary of data:

- *RemBind*® Plus removed shorter chain PFASs more effectively than activated carbon
- 60 minute contact time is optimal
- Estimated PFOS adsorption capacities:
  - ~2,000 µg/g for *RemBind*® Plus
  - ~1,000 µg/g for activated carbon

# Summary

*For every zone of your plume, we've got you covered!*

- *RemBind*® Outperformed activated carbon in binding shorter chain compounds PFBS/PFBA
- Showed double the adsorption capacity of the activated carbon
- Strongly bound to PFOS and PFOA in soil/water
- Bound 18 PFAS additional compounds to varying degrees



# PerfluorAd®

- Developed by Cornelsen and Fraunhofer Institute
- Surface active liquid ingredient
- Economical, fully proven at scale
- Removes a full range of PFASs from water



# *PerfluorAd<sup>®</sup> Chemistry*

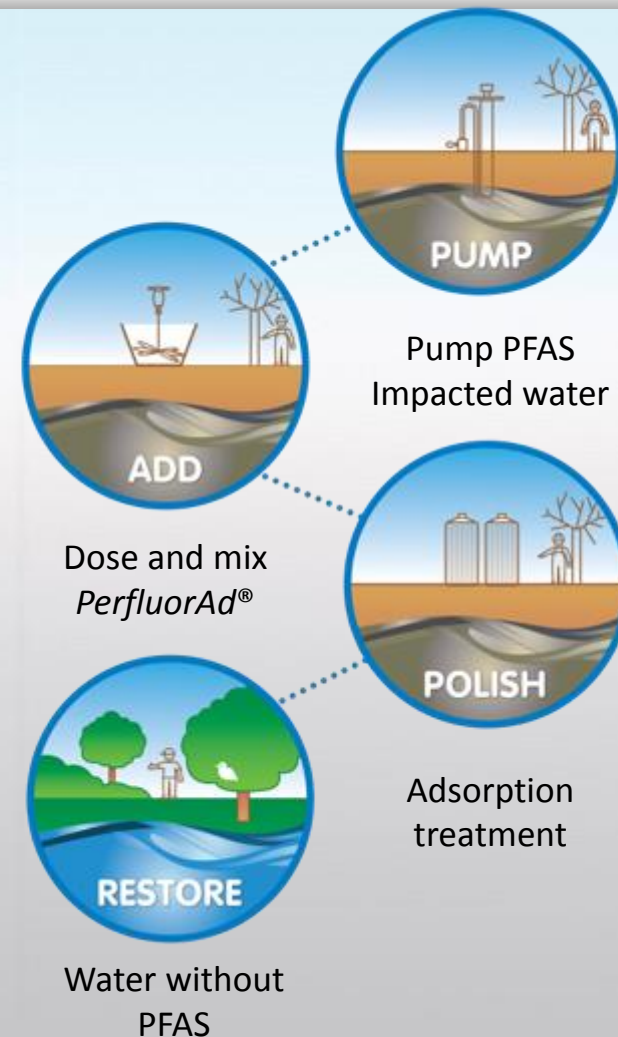
*For every zone of your plume, we've got you covered!*

- No chemical process between *PerfluorAd<sup>®</sup>* and PFASs
- No transformational PFAS products are formed
- Other organic substances not adsorbed by *PerfluorAd<sup>®</sup>*
- *PerfluorAd<sup>®</sup>* is non-toxic and biodegradeable

# PerflourAd<sup>®</sup> Principle of Operation

*For every zone of your plume, we've got you covered!*

- Added to PFASs contaminated water in stirring reactor
- Dosing rate adjustable to PFAS concentration or target
- Micro-flocs are generated
- Flocs removable by precipitation & filtration
- Removes up to 98% of PFAS contaminants prior to polishing
- Non-detect concentrations with adsorbent polishing





# PerfluorAd® System Operation

*For every zone of your plume, we've got you covered!*



*PerfluorAd® Stirring Reactors*



Mobile Treatment System



# *PerfluorAd® - renewable, reusable, extendable*

*For every zone of your plume, we've got you covered!*

Treatment systems mobile

Used on fire fighting water treatment, municipal water systems or groundwater treatment

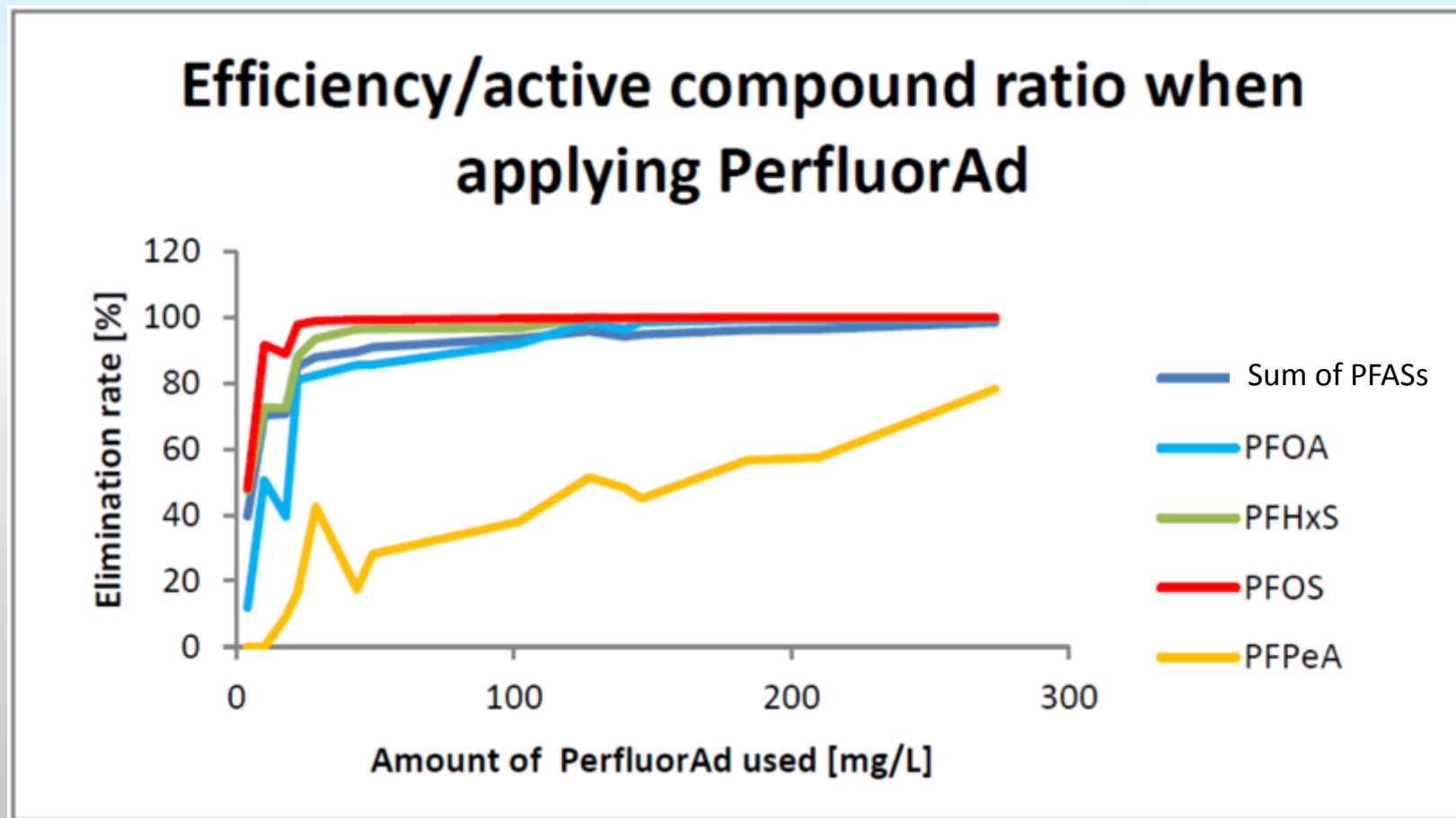
Dosing rates and residence times can be adjusted for different inlet conditions



Mobile Treatment System

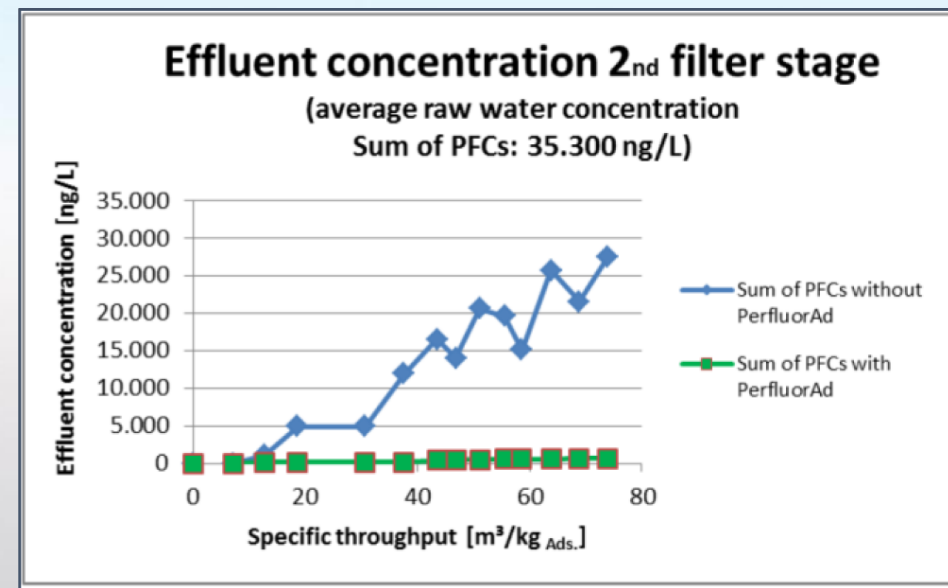
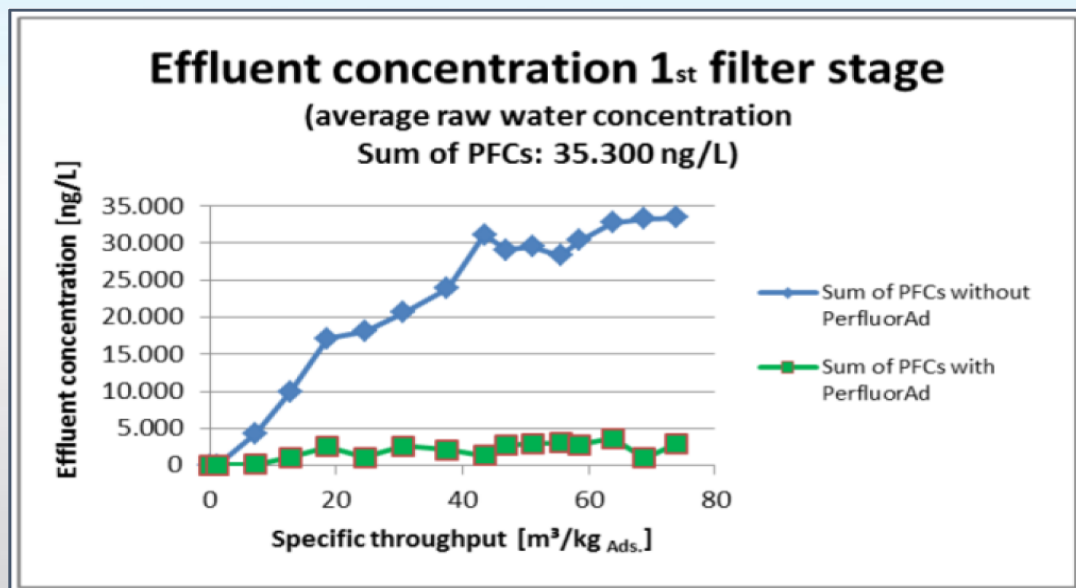
# PerfluorAd® Performance

*For every zone of your plume, we've got you covered!*



# Treatment with / without PerfluorAd<sup>®</sup>

*For every zone of your plume, we've got you covered!*



# *PerfluorAd<sup>®</sup> Benefits*

*For every zone of your plume, we've got you covered!*

- Removes bulk of PFC/PFAS contaminants prior to polishing
- No PFAS breakdown components
- Significantly extends life of activated carbon
- Thereby significantly reduces AC use
- Significantly minimizes disposal costs

# PerfluorAd® Case Study

## Dusseldorf and Nuremburg Airport Test Sites



### Nuremberg

- BTEX: Ethylbenzene & Xylene
- VOC: cDCE, TCE, VC
- Hydrocarbons (C5-C10, > C 10) & PAH (traces)

Compound	unit	max	min	average
pH		6,1	5,1	5,6
iron	mg/l	33,0	13,0	26,0
VOC	µg/l	49,0	15,0	27,0
BTEX	µg/l	15,0	0,0	4,0
DOC	mg/l	15,0	7,0	9,0
PFC	µg/l	777,0	144,0	357,0

# Nuremburg PFAS Chemistry

*For every zone of your plume, we've got you covered!*

PFC/PFAS	unit	average value	percentage
PFBA	µg/l	6,17	1,46
PFPeA	µg/l	10,87	2,57
PFHxA	µg/l	26,50	6,26
PFHpA	µg/l	4,33	1,02
PFOA	µg/l	9,52	2,25
PFNoA	µg/l	0,15	0,04
PFDeA	µg/l	0,04	0,01
PFUnA	µg/l	<0,01	
PFDoA	µg/l	<0,01	
PFOSA	µg/l	0,20	0,05
PFBS	µg/l	13,27	3,13
PFHxS	µg/l	115,78	27,33
PFHpS	µg/l	8,62	2,04
PFOS	µg/l	206,39	48,72
PFDeS	µg/l	<0,01	
4:2 FTS	µg/l	0,14	0,03
6:2 FTS	µg/l	17,72	4,18
8:2 FTS	µg/l	3,98	0,94

**Sum PFASs**

**Average 357 µg/l**

**Maximum 777 µg/l**

**Minimum 144 µg/l**

# Nuremburg Project Background

*For every zone of your plume, we've got you covered!*

- Treatability Study
- Pilot Test – Sept. through Nov. 2014
- Data evaluation
  - PerfluorAd found as most economical technique
  - PerfluorAd selected for full scale
- Full scale Installation Sept. 2015



# Nuremburg PerfluorAd<sup>®</sup> System

*For every zone of your plume, we've got you covered!*

- Flow rate 9 gpm
- Remediation target 0.3 µg/l for PFOS, PFOA & PFHxS (sum)
- Plus max 0.23 µg/l PFOS
- Remote control
- 1 or 2 site visits per week

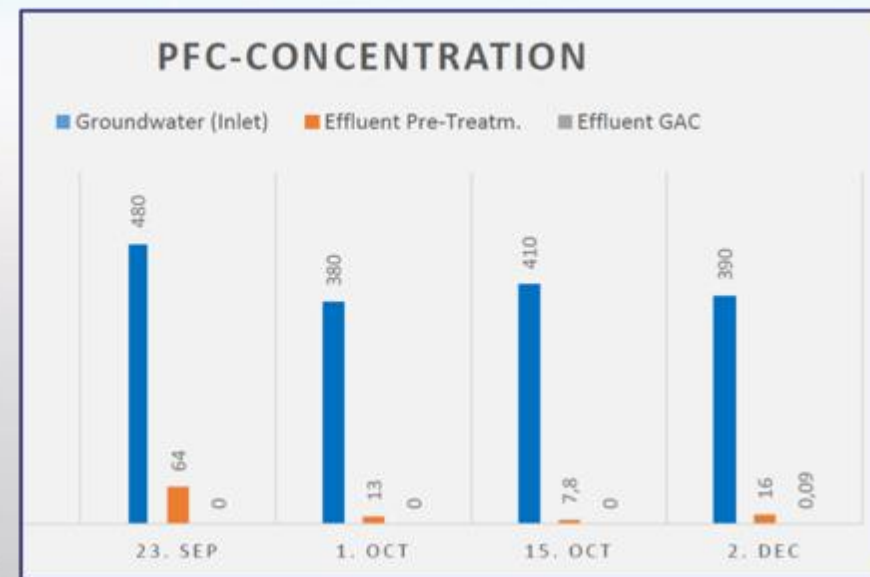


# Nuremburg PerfluorAd® Performance Results

*For every zone of your plume, we've got you covered!*

## PFAS Treatment

Sampling Date	Groundwater (Inlet)	Effluent Pre-Treatm.	Effluent GAC	Removal PerfluorAd
23. Sep	480	64	0	86,7
1. Oct	380	13	0	96,4
15. Oct	410	7,8	0	98,1
2. Dec	390	16	0,09	95,9



# *PerfluorAd<sup>®</sup> and GAC Life Extension*

*For every zone of your plume, we've got you covered!*

## GAC and PCE

- Loading of 12%
- Residence time 10 minutes

## GAC and PFASs

- Loading of 0.03%
- Residence time 40 minutes

# *PerfluorAd<sup>®</sup> & GAC Life Extension*

*For every zone of your plume, we've got you covered!*

- To capture same amount of PFAS & PCE .....
- = 12% / 0.03% times the residence time ratio of 4 = 1600
- 1600 times amount of GAC to treat PFAS vs PCE (= concentration)
- Removing up to 98% of PFASs with *PerfluorAd<sup>®</sup>* **critical** to O&M costs

# *Anticipated disposal type / volume requirements*

*For every zone of your plume, we've got you covered!*

per 1,000 gallons of water with 500  $\mu\text{g/l}$  PFASs concentration

0.42 lbs. floc per 1,000 gallons

**1 drum per million gallons**

Using GAC ~30 drums per million gallons

# PerfluorAd<sup>®</sup> Summary

*For every zone of your plume, we've got you covered!*



PROVEN

- Removes up to 98% of PFAS contaminants prior to polishing



EFFECTIVE

- Non-toxic, biodegradable, no PFAS breakdown products



SAFE

- Dosing rate adjustable to PFAS concentrations
- Reduces costs, dramatically extends life of adsorbent media
- Minimizes disposal costs

# Thank You!

*For every zone of your plume, we've got you covered!*



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